

PG 1115+080: variations of the A2/A1 flux ratio and new values of the time delays

V.S.Tsvetkova^{1*}, V.G.Vakulik^{1,2}, V.M.Shulga¹, R.E.Schild³, V.N.Dudinov^{1,2},
A.A.Minakov¹, S.N.Nuritdinov⁵, B.P.Artamonov⁵, A.Ye.Kochetov^{1,2}, G.V.Smirnov²,
A.A.Sergeyev^{1,2}, V.V.Konichek², I.Ye.Sinelnikov², A.P.Zheleznyak², V.V.Bruevich⁴,
R.Gaysin⁵, T.Akhunov⁵, O.Burkhonov⁵

¹*Institute of Radio Astronomy of Nat.Ac.Sci. of Ukraine, Krasnoznamennaya 4, 61002 Kharkov, Ukraine*

²*Institute of Astronomy of Kharkov National University, Sumskaya 35, 61022 Kharkov, Ukraine*

³*Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, U.S.A.*

⁴*Sternberg Astronomical Institute, Universitetski Ave. 13, 119899 Moscow, Russia*

⁵*Astronomical Institute of Ac.Sci.of Uzbekistan, Astronomicheskaya 33, 100052 Tashkent, Uzbekistan*

Accepted ... Received ...; in original form December 24, 2009

ABSTRACT

We report the results of our multicolor observations of PG 1115+080 with the 1.5-m telescope of the Maidanak Observatory (Uzbekistan, Central Asia) in 2001–2006. Monitoring data in filter *R* spanning the 2004, 2005 and 2006 seasons (76 data points) demonstrate distinct brightness variations of the source quasar with the total amplitude of almost 0.4 mag. Our *R* light curves have shown image C leading B by 16.4d and image (A1+A2) by 12d that is inconsistent with the previous estimates obtained by Schechter et al. in 1997 – 24.7d between B and C and 9.4d between (A1+A2) and C. The new values of time delays in PG 1115+080 must result in larger values for the Hubble constant, thus reducing difference between its estimates taken from the gravitational lenses and with other methods. Also, we analyzed variability of the A2/A1 flux ratio, as well as color changes in the archetypal “fold” lens PG 1115+080. We found the A1/A2 flux ratio to grow during 2001–2006 and to be larger at longer wavelengths. In particular, the A2/A1 flux ratio reached 0.85 in filter *I* in 2006. We also present evidence that both the A1 and A2 images might have undergone microlensing during 2001–2006, with the descending phase for A1 and initial phase for A2. We find that the A2/A1 flux ratio anomaly in PG 1115 can be well explained both by microlensing and by finite distance of the source quasar from the caustic fold.

Key words: cosmology: gravitational lensing – galaxies: quasars: individual: PG 1115+080.

1 INTRODUCTION

Gravitationally lensed quasars are known to potentially provide estimates of the Hubble constant H_0 from measurements of the time delays between the quasar intrinsic brightness variations seen in different quasar images (Refsdal 1964). Since a phenomenon of gravitational lensing is controlled by the surface density of the total matter (dark plus luminous), it provides a unique possibility both to determine the value of H_0 and to probe the dark matter content in lensing galaxies and along the light paths in the medium between the quasar and observer.

By now the time delays have been measured in about 20 gravitationally lensed quasars resulting in the values of H_0 that are generally noticeably less than the most recent estimate of H_0 obtained in the HST Hubble Constant Key Project with the use of Cepheids – $H_0 = 72 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Freedman et al. 2001). This discrepancy

is large enough and, if the Hubble constant is really a universal constant, needs to be explained. A detailed analysis of the problem of divergent H_0 estimates inherent in the time delay method, and the ways to solve it can be found, e.g., in Keeton & Kochanek (1997), Saha & Williams (1997), Kochanek (2002), Kochanek & Schechter (2004) and Schechter (2005), Read et al. (2007), and in many other works.

The main sources of uncertainties in determining H_0 are:

- low accuracy of the time delay estimates caused by poorly sampled and insufficiently accurate light curves of quasar components, as well as by microlensing events and, as a rule, by low amplitudes of the quasar intrinsic variability;
- difference in the values of cosmological constants adopted in deriving H_0 ;
- invalid models of mass distribution in lensing galaxies.

The way to reduce the effect of the first source of errors is clear enough: more accurate and better sampled light curves of a

* E-mail: tsvetkova@astron.kharkov.ua

sufficient duration are needed. A choice of the cosmological model is usually just indicated - this is mostly a question of agreement. As to the third item, here the problem of estimating the Hubble constant encounters the problem of the dark matter abundance in lensing galaxies.

The problem of determining the Hubble constant from the time delay lenses is known to suffer from the so-called central concentration degeneracy, which means that, given the measured time delay values, the estimates of the Hubble constant turn out to be strongly model-dependent. In particular, models with more centrally concentrated mass distribution (lower dark matter content) provide higher values of H_0 , more consistent with the results of the local H_0 measurements than those with lower mass concentration towards the center (more dark matter). Moreover, it has long been noticed that the time delays are sensitive not only to the total radial mass profiles of lensing galaxies, but also to the small perturbations in the lensing potential (e.g., Blandford & Narayan 1986, Witt et al. 2000, Oguri 2007). It is interesting to note that this effect has been recently proposed as a new approach to detect dark matter substructures in lensing galaxies (Keeton & Moustakas 2009).

The Hubble constant – central concentration degeneracy is a part of the well known total problem of lensing degeneracies: all the lensing observables, even if they were determined with zero errors, are consistent with a variety of the mass distribution laws in lensing galaxies. A strategy for solving this non-uniqueness problem could be a search through a family of lens models that are capable of reproducing the lensing observables (Williams & Saha 2000, Oguri et al. 2007). Then many models can be run in order to infer a probability density for a parameter under investigation, e.g. for H_0 (Williams & Saha 2000). The most recent studies (Saha et al. 2006, Read et al. 2007) have shown that, in such an approach, the discrepancy between the H_0 value determined from lensing and with other methods can be substantially reduced if non parametric models for mass reconstruction are used, which can provide much broader range of models as compared to the parametric ones.

In defining priors on the allowed space of lens models, it is naturally to assume that lensing galaxies in the time delay lenses are similar in their mass profiles to other early-type ellipticals, that are presently believed to be close to isothermal and admit the presence of the cold dark matter haloes. The isothermal models are also consistent with stellar dynamics, as well as with the effects of strong and weak lensing.

The quadruply lensed quasars are known to be more promising for solving these problems as compared to the two-image lenses since they provide more observational constraints to fit the lens model. Ten astrometric constraints can be presently regarded as measured accurately enough for most systems. This especially concerns the relative coordinates of quasar images. As to the lensing galaxy, its less accurate coordinates are often the only reliable information about the lensing object known from observations, with other important characteristics being derived indirectly. This situation is inherent, e.g. in PG 1115+080 with its faint, 0.31- redshift galaxy. Of other observational constraints, the time delays and their ratios are very important. In quadruple lenses, the time delay between one of the image pairs is usually used to determine H_0 , while the other ones form the H_0 -independent time delay ratios to constrain the lens model, (Keeton & Kochanek 1997).

It has long been known that the observed positions of multiple quasar macroimages are well predicted by smooth regular models of mass distribution in lensing galaxies, while their brightness ratios are reproduced by such models poorly, (e.g., Kent and Falco 1988, Kochanek 1991, Mao & Schneider 1998). The first system-

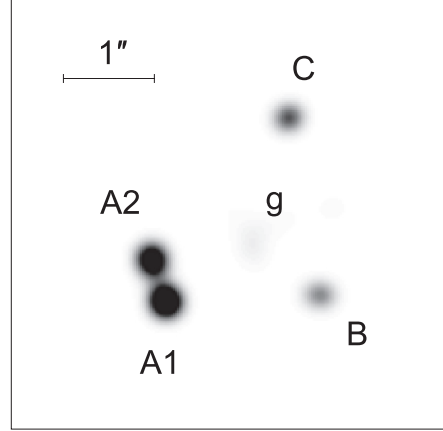


Figure 1. PG1115+080 from observations in filter R with the 1.5-m telescope of the Maidanak Observatory. The image was obtained by averaging of six frames from a series obtained in February 24, 2004, with a subsequent Richardson-Lucy processing.

atic analysis of this problem called "flux ratio anomalies" was made by Mao & Schneider (1998), who assumed that the anomalies of mutual fluxes of the components in some lenses can be explained by the presence of small-scale structures (substructures) in lensing galaxies or somewhere near the line of sight.

A popular model of forming hierarchical structures in the Universe with a dominant content of dark matter is currently known to poorly explain the observed distribution of matter at small scales. In particular, the expected number of satellite galaxies with masses of the order of $M_G \approx 10^8 M_\odot$ remained after the process of hierarchical formation is completed, is an order of magnitude larger than a number of dwarf galaxies with such masses actually observed within the Local Group (Klypin et al. 1999, Moore et al. 2001). One of the solutions of this contradiction is a suggestion that some substructures, especially those with low masses, are not luminous.

Metcalf and Madau (2001) were the first to note that the dark matter paradigm can naturally explain existence of substructures in galaxies lensing the remote quasars, as proposed by Mao and Schneider (1998) to interpret the anomalies of mutual fluxes of quasar macroimages, and vice versa, confirmation of substructures with masses from $10^6 M_\odot$ to $10^8 M_\odot$ is capable of removing the contradiction between the predicted number of the low-mass satellite galaxies and that one actually observed. The idea turned out to be intriguing and was immediately taken up, (Bradač et al. 2002, Chiba 2002, Dalal & Kochanek 2002, Keeton 2001, Metcalf & Zhao 2002). Investigation of flux ratio anomalies in gravitationally lensed quasars is presently believed to be a powerful tool in solving the problem of the dark matter abundance in the Universe. It is intensively discussed in numerous recent publications (Congdon & Keeton 2005; Keeton et al. 2003, 2005; Kochanek & Dalal 2004; Mao et al. 2004; Miranda & Jetzer 2007; Pooley et al. 2006, 2007, 2009; Morgan et al. 2008).

In Sec. 3 we report our measurements of the A2/A1 flux ratios in filters V , R and I from our data obtained in 2001, 2002 and 2004-2006 at the Maidanak Observatory and analyse their behaviors in time and in wavelength. In Sec. 4, we analyze the new estimates of the time delays between the PG 1115+080 images, obtained from our monitoring in the R filter during 2004-2006 and reported in Vakulik et al. (2009). The new values differ noticeably from those reported by Schechter et al. (1997) and Barkana (1997). In Sec. 5, we discuss our results and their possible effect on selecting an ade-

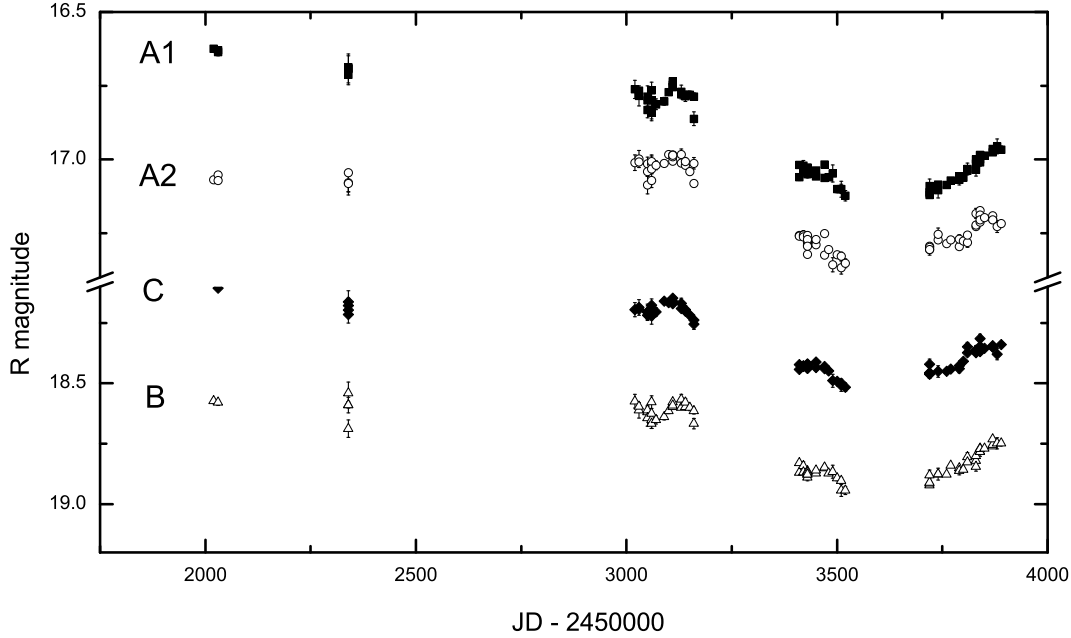


Figure 2. The light curves of PG 1115+080 A1, A2, B, C from observations in filter *R* with the 1.5-m telescope of the Maidanak Observatory in 2001, 2002, 2004, 2005 and 2006.

quate lens model for PG 1115+080 and estimating the value of the Hubble constant.

2 OBSERVATIONS

The quadruply imaged quasar PG 1115+080 is one of the most promising candidates both to investigate the dark matter problem and to determine the H_0 value from measurements of the time delays between the image components. The source with a redshift of $z_S = 1.722$ is lensed by a galaxy with $z_G = 0.31$ (Henry & Heasley 1986, Christian et al. 1987, Tonry 1998), which forms four quasar images, with an image pair A1 and A2 bracketing the critical curve very close to each other. It is the second gravitationally lensed quasar discovered over a quarter of century ago, at first as a triple quasar (Weymann et al. 1980). Hege et al. (1980) were the first to resolve the brightest image component into two images separated by 0.48 arcsec. Further observations (Young et al. 1981, Vanderriest et al. 1986, Christian et al. 1987, Kristian et al. 1993, Courbin et al. 1997) have provided positions of quasar images and information about the lensing object, which allowed construction of a macrolens model (e.g., Keeton, Kochanek & Seljak 1997). In particular, Keeton & Kochanek (1997) have shown that the observed quasar image positions and fluxes and the galaxy position can be fit well by an ellipsoidal galaxy with an external shear rather than by only an ellipsoidal galaxy, or by a circular galaxy with an external shear. They noted that a group of nearby galaxies detected by Young et al. (1981) could provide the needed external shear.

Observations of PG 1115+080 were started at the 1.5-meter telescope of the high-altitude Maidanak Observatory (Central Asia, Uzbekistan) in 2001. An image scale of $0.26''/\text{pix}$ was available at the f/8 focal plane with a scientific BroCam CCD camera having a SITe ST 005A 2030 x 800 chip. The CCD images were usually taken in series consisting of 2 to 10 frames for the *R* filter and of 2 to 6 frames for *V* and *I*. To provide higher photometric accuracy, we averaged the values of magnitudes estimated from indi-

vidual frames. The seeing varied from $0.75''$ to $1.3''$ [the full width at half-maximum (FWHM) of images of the reference stars B and C according to designation by Vanderriest et al. (1986)]. The analysis of photometry shows no significant dependence of the photometry errors on seeing, excepting the FWHM noticeably exceeding $1.3''$. Occasional frames with such values of the FWHM were excluded from processing.

In Fig. 1 we show one of the best images of PG 1115+080 obtained through the *R* filter. For better view, the image was restored with an algorithm similar to that proposed by Richardson (1972) in optics and independently by Lucy (1974) in astronomy (the Richardson-Lucy iterative method).

Our algorithm for photometric image processing is similar to that applied to Q2237+0305 and described in detail by Vakulik et al. (2004). The light curves of PG 1115+080A1,A2,B,C in filter *R* for the time period from April 2001 to June 2006 are shown in Fig. 2. The photometry in the *V*, *R* and *I* filters is presented in Tables 6-8.

Unfortunately, observations were not carried out in 2003, and the data are very scanty for the 2001 and 2002 seasons in all the three filters. The most numerous data were obtained in filter *R*, especially in 2004 (23 nights), 2005 (27 nights) and in 2006 (24 nights). The data demonstrate noticeable variations of the quasar brightness, with the total amplitude reaching approximately 0.4 mag in 2004-2006, and smaller amplitudes of about 0.05 mag on a time-scale of two months, which are clearly seen in all the four light curves in 2004. The time delays between the light curves of the C and B, C and A1 (or A2) images can be easily seen from a simple visual inspection of the *R* light curves, therefore, the data obtained in 2004-2006 in filter *R* seem to have good prospects for obtaining reliable estimates of the time delays in PG 1115+080.

Thanks to the spatially resolved photometry of the A1 and A2 image pair in filters *V*, *R* and *I*, our data have made it possible to measure flux ratios for these components for five seasons of observations, and to study their behavior in time and in wavelength.

Table 1. Estimates of the A2/A1 brightness ratios in PG 1115+030 for the time period 1980-2006 from all available data.

Date	A2/A1 flux ratio	Spectral range	Instrument	Reference
1980 June	0.83	<i>V</i>	MMT	Hege et al. (1980)
1981 April 30	1.0	<i>B</i>	CFHT	Vanderriest (1986)
1983 March 8	1.0	<i>V</i>	– ” –	– ” –
1984 March 26	0.95	<i>B</i>	– ” –	– ” –
1985 March 16	0.75	<i>B</i>	– ” –	– ” –
1985 March 19	0.79	<i>V</i>	– ” –	– ” –
1986 February 19	0.79	<i>V</i>	CFHT	Christian (1987)
– ” –	0.8	<i>R</i>	– ” –	– ” –
– ” –	0.79	<i>B</i>	– ” –	– ” –
1989 April	0.68	<i>I</i>	CFHT	Schechter (1993)
1991 March 3	0.66	<i>V</i>	HST	Kristian (1993)
– ” –	0.7	<i>I</i>	– ” –	– ” –
1992 April	0.67	<i>I</i>	Hiltner	Schechter 1993
– ” –	0.69	<i>V</i>	– ” –	– ” –
– ” –	0.72	<i>I</i>	CTIO	– ” –
– ” –	0.68	<i>V</i>	– ” –	– ” –
1993 April	0.69	<i>I</i>	Hiltner	– ” –
– ” –	0.63	<i>V</i>	– ” –	– ” –
1995 December 20	0.66	<i>V</i>	Magellan	Pooley et al. (2006)
1996 June 7	0.68	<i>I</i>	NOT	Courbin et al. (1997)
1997 November 17	0.64	<i>H</i>	HST	Impey et al. (1998)
?	0.52	<i>V</i>	HST	Morgan et al. (2008)
?	0.67	<i>I</i>	– ” –	– ” –
?	0.63	<i>H</i>	– ” –	– ” –
2001 March 26	0.66	<i>V</i>	Magellan	Pooley et al. (2006)
2001 April 20-27	0.74	<i>V</i>	1.5m(Maidanak)	This work
– ” –	0.67	<i>R</i>	– ” –	– ” –
– ” –	0.72	<i>I</i>	– ” –	– ” –
2002 March	0.76	<i>V</i>	– ” –	– ” –
– ” –	0.71	<i>R</i>	– ” –	– ” –
– ” –	0.72	<i>I</i>	– ” –	– ” –
2004 February 22	0.81	Sloan <i>i'</i>	Magellan	Pooley et al.(2006)
2004 May 5-6	0.93	11.67 μ m	Subaru	Chiba et al. (2005)
2004 Jan.17-June 8	0.79	<i>V</i>	1.5m Maidanak	This work
– ” –	0.81	<i>R</i>	– ” –	– ” –
2004 Apr.11-June 8	0.83	<i>I</i>	– ” –	– ” –
2005 June 07	0.81	Sloan <i>i'</i>	Magellan	Pooley et al. (2006)
2006 Jan.5-Apr.15	0.8	<i>V</i>	1.5m Maidanak	This work
2006 Jan.5-June 2	0.83	<i>R</i>	– ” –	– ” –
2006 Jan.5-Apr.15	0.85	<i>I</i>	– ” –	– ” –

As is noted above, deviations of flux ratios in quasar macroimages from the theoretical predictions (flux ratio anomalies) are presently believed to be diagnostic for detection of substructures in lensing galaxies, which may represent the dark matter.

3 THE A2/A1 FLUX RATIOS

The idea to detect substructures in lensing galaxies using the anomalies of flux ratios is based on fundamental relationships between coordinates and magnifications of the quasar images, which result from the general lens equation (Schneider, Ehler & Falco, 1992). These relationships have been obtained for the first time by Schneider and Weiss (1992) and Mao (1992) for several “smooth” distributions of lensing potential. In principle, the lens equation is capable of providing six independent relationships between the coordinates and magnifications for a quadruple lens, but only one of them can be checked with the data of observations. This is the well-known magnification sum rule for a source within a macrocaustic

cusps, when three close images emerge: magnification of the central image must be equal to the sum of magnifications of two outer images (Schneider & Weiss 1992). When the source lies near a caustic fold, two images of the same brightness must arise (Keeton, Gaudi and Petters 2005, KGP hereafter). Since the absolute values of magnifications in macroimages are unknown (the unlensed quasar cannot be observed), Mao & Schneider (1998) proposed to use the dimensionless quantities

$$R_{cusp} = \frac{|\mu_1| - |\mu_2| + |\mu_3|}{|\mu_1| + |\mu_2| + |\mu_3|} = \frac{F_1 - F_2 + F_3}{F_1 + F_2 + F_3} \quad (1)$$

for three images emerging when the source is in a caustic cusp, and

$$R_{fold} = \frac{|\mu_m| - |\mu_s|}{|\mu_m| + |\mu_s|} = \frac{F_m - F_s}{F_m + F_s} \quad (2)$$

for the case when the source is at the caustic fold. Indices *m* and *s* in the second expression denote the images at the minimum and saddle points of the Fermat surface.

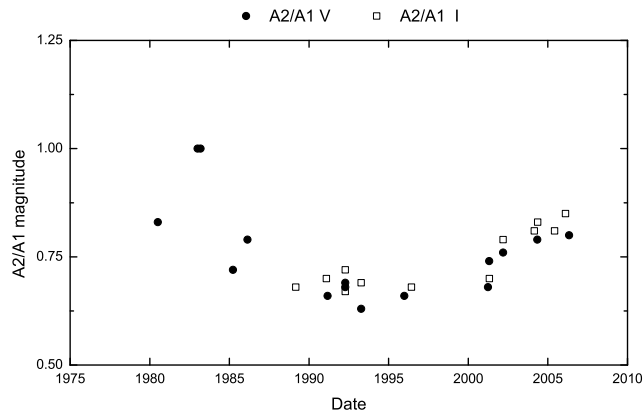


Figure 3. A history of the A2/A1 flux ratios in PG 1115+080 from the data in filters V and I as listed in Table 1.

Ideally, cusp relation $R_{cusp} = 0$ and fold relation $R_{fold} = 0$ hold only when the source lies exactly at the caustic cusp or fold, respectively. In real lenses these relations hold only approximately. KGP(2003, 2005) fulfilled a detailed study of asymptotic behaviours of the cusp and fold relations and calculated probability distributions of R_{fold} values for several smooth lens models. The value of deviation of R_{cusp} and R_{fold} from zero can be regarded as a measure of probability for the lensing potential to have substructures on scales smaller than the separation between the closest images (KGP 2003, 2005). KGP (2005) warn, however, that for fold lenses, the observed violation of the fold relation may just mean that the source is far enough from a caustic fold.

It should be noted that, in principle, the observed anomalies of brightness ratios in images of gravitationally lensed quasars can be explained by other factors, such as microlensing by compact bodies and the effects of propagation phenomena in the interstellar medium (extinction and scattering, scintillations). These factors are studied in details by Kochanek & Dalal (2004). They concluded that substructures of cold dark matter is the best explanation for the flux ratio anomalies in some quadruply lensed quasars. They reminded also that, as was stated for the first time by Mao & Schneider (1998), the fluxes of highly magnified saddle images are very sensitive to small gravitational perturbations as compared to low-magnification images and, even more importantly, these perturbations bias the fluxes towards demagnification, as was also noted by Schechter & Wambsganss (2002).

3.1 Behavior of the flux ratios in time

The A1+A2 image pair in PG 1115+080 consists of a highly magnified minimum point image (A1) and saddle point image (A2) situated symmetrically with respect to the fold caustic very close to each other. According to theoretical expectations (e.g. Schneider et al. 1992), the ratio of their fluxes must be close to 1.

There are numerous measurements of the A2/A1 brightness ratio in PG 1115+080 made at different spectral ranges and at different epochs since 1980, which we tried to assemble in Table 1. Some of these data have been used by Pooley et al. (2009) to analyse a long-term history of the A2/A1 variations in the optical band and to compare with the X-ray data, (see, e.g., Pooley et al. 2006, 2007, 2009). Fig. 2 from the work by Pooley et al. (2009) demonstrates changes in the A2/A1 optical flux ratio during the time period from 1980 to 2008, and much more dramatic changes of this

ratio in X-rays. Pooley et al. (2009) noted that, according to all the observations since the system discovery, the A2/A1 flux ratio varied within 0.65-0.85. They did not specify the optical spectral bands for the data in their Fig.2, however, but it looks like they are for filter V.

In our Table 1, the telescopes and filter bands are indicated for all estimates of the A2/A1 flux ratios. The table does not contain the results of the Chandra X-rays observations, which exhibited strong flux ratio anomaly and can be found, e.g., in Pooley et al. (2006, 2007, 2008). The data in Table 1 are also supplemented by the estimates of the A2/A1 flux ratios obtained from our photometry (Tables 5-7). Flux ratios in filters V and I from Table 1 are displayed in Fig. 3. These flux ratios behave similarly in time for both filters, and in general features resemble fig. 2 from Pooley et al. (2008). Based upon their fig. 2, Pooley et al. (2008) argue that the optical flux ratio anomaly in PG 1115+080 is slight and "nearly constant in time". Our analysis described below have shown, however, that it is not quite so. Our Fig. 3, where the available previous data in V and I are supplemented by our measurements, shows that variations of the A2/A1 flux ratio in time are indeed rather small and slow. However, even if we exclude a marginal value for the date 1983, March 8 (Vanderriest et al. 1986), which equals 1 with the uncertainty of 0.1, we will have the A2/A1 flux ratio varying in some regular manner with the amplitude of about 0.15 during the last 25 years. Somewhere between 1991 and 1996, the ratio reached its minimal value of about 0.65 in filter V, and increased up to 0.8 by 2006. It should be noted that the fact that A2/A1 flux ratio varies in time is in itself an argument in favour of microlensing as the main reason for the anomalous flux ratio in PG1115+080. Also, it should be mentioned that the A2/A1 flux ratio is slightly but steadily higher in filter I than in V.

To determine which component (or components) exactly underwent microlensing, we addressed only our data as more homogeneous ones, and analysed behaviors in time of the long-term constituents of the A2-A1, C-A1, B-C and C-A2 magnitude differences for filters R and I. These difference light curves in filter R are shown in Fig. 4. We did not correct the individual light curves for the time delays, which are small as compared to the characteristic time-scale of quasar flux variations. This might result only in some increase of the data points scatter with respect to the approximating curves, which are the second-order polynomials in Fig.4.

The largest decrease of the magnitude difference is for the A2-A1 image pair - about 0.23 mag during 2001-2005. Pair C-A1 shows an almost linear decrease of the magnitude difference in time, with only 0.12 mag during 2001-2005. Since the mutual brightness of images B and C was almost invariable in 2001-2006, one might conclude that it is an image A1 that became fainter during this time period. But the C-A2 magnitude difference curve shows however, that, in addition to the obvious dimming of image A1, brightening of image A2 makes a certain contribution to the decrease of the A2-A1 magnitude difference in 2001-2005.

Therefore, we can conclude that a decay of A1 and brightening of A2 took place simultaneously in PG 1115+080 during 2001-2006. We may also conclude that it is the A1 image that underwent microlensing in the previous years, with the maximum near 1992-1995, as seen from Fig. 2, and the final phase in 2006 or, perhaps, later. With the previous data taken into account (see Fig. 3 and Table 1), the total time-scale of the 0.3-magnitude event is about 25 years. Image A2 underwent microlensing as well, with its rising branch occurring in 2001-2005. The brightening of image A2 reached about 0.14 mag during this time period, while the total brightening in the whole event may be larger. In calculation of

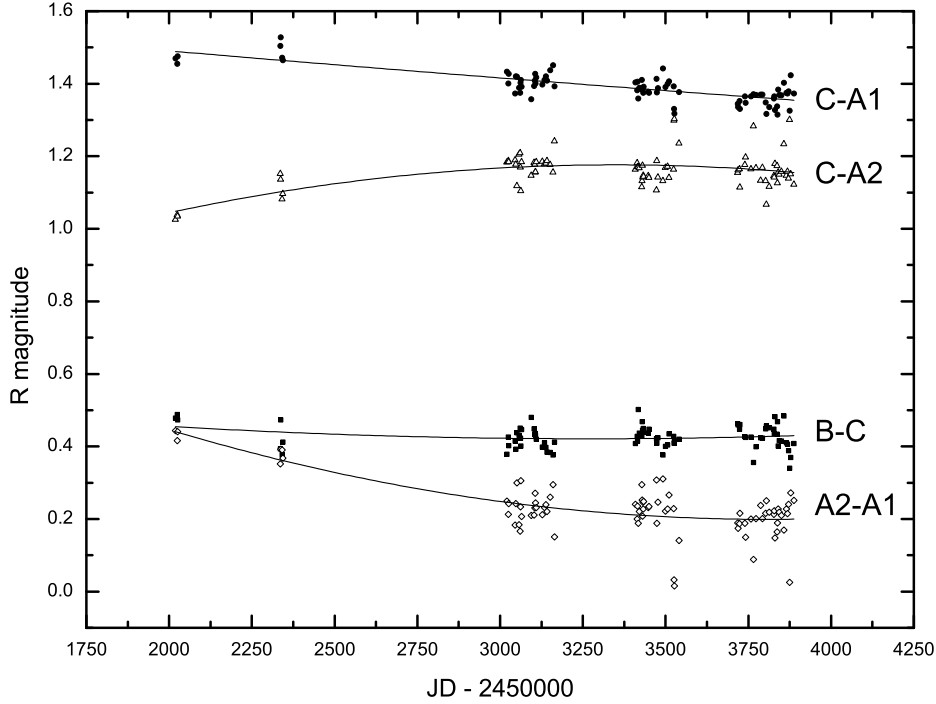


Figure 4. Behaviors of the C-A1, C-A2, B-C and A2-A1 magnitude differences in time from the results of our photometry in filter *R*; approximation by the second-order polynomials is shown.

Table 2. Flux ratios in PG 1115+080 as predicted by the most recent lens models and determined from the results of our photometry in 2006 (filter *I*); the uncertainty of our flux ratio estimates is 0.02 for all ratios.

Lens model	A2/A1	B/A1	C/A1	B/C
Chiba (2002)	0.92	0.22	0.28	0.8
Chiba (2005)	0.92	0.22	0.28	0.79
Pooley(2006)	0.96		0.26	0.67
Pooley(2007)	0.92	0.21	0.27	0.78
This work	0.85	0.19	0.29	0.68

the time delays, more subtle variations of the magnitude differences during 2004–2006 were found, (see Sec. 4.1).

It should be noted that our results are well consistent with measurements of the A1–A2 magnitude difference presented in Morgan et al. (2008), who reported approximately 0.2-mag growth of this quantity during 2001–2006. However, they do not present the magnitude differences between other images and A1 or A2 separately, which has led us to a conclusion about the final phase of microlensing in image A1 and, seemingly, the initial phase of a microlensing event in image A2. This conclusion is also indirectly confirmed by the results of Pooley et al. (2009), who reported a dramatic rise in the X-ray flux from image A2 between 2001 and 2008. Larger microlensing amplitudes at shorter wavelengths are often detected for many lensed quasars and are known to be naturally explained by smaller effective sizes of quasars at shorter wavelengths.

The observed time-scales and amplitudes of the microlensing brightness fluctuations are known to depend on the relative velocity of a quasar and lensing galaxy, and on the relationship between the source size and the Einstein ring radius of a microlens. For PG1115+080, the expected duration of a microlensing event is es-

timated to be of the order of 10 to 20 years for the subsolar mass microlens (Chiba 2005), well consistent with that in image A1 observed in 1980–2006.

Thus, if our interpretation of the observed brightness variations in the A1, A2, B and C images is valid, then the A2/A1 flux ratio would be expected to approach its undisturbed value in a few years, unless a new event takes place in at least one image. Our estimates of the A2/A1, B/A1, C/A1 and B/C flux ratios calculated from the photometry data of 2006, are presented in Table 2 along with the model predictions by Chiba (2002), Chiba et al. (2005), Pooley et al. (2006, 2007). The ratios for filter *I* are presented, where the effect of microlensing is expected to be minimal as compared to *V* and *R*. As is seen from Table 2, the A1/A2 flux ratio is still less than predicted by the most recent lens models. However, when expressed in terms of R_{fold} , it would equal 0.08, which means that, according to simulations of KGP (2005), this flux ratio is within a region admissible by a smooth lensing potential model for the finite source distances from the caustic fold, that is, it is not anomalous in the sense implied by Mao&Schneider (1998).

3.2 Color Changes in PG1115+080

We have also made use of our multicolor observations to analyze behaviors of the *V* – *I* color indices of image components, which were shown to be indicative of the microlensing nature of brightness changes for at least the Q2237+0305 quasar (Vakulik et al. 2004). Since only 16 data points were available to build the *V* – *I* versus *R* dependency for each image component, we did not build them for the components separately, but combined the data into two sets, for A1+A2 and B+C image pairs. The resulting diagrams are presented in Fig. 5. In order to eliminate the magnitude difference and possible permanent color difference between the components in each pair, we shifted the data points in both plots along the *R*

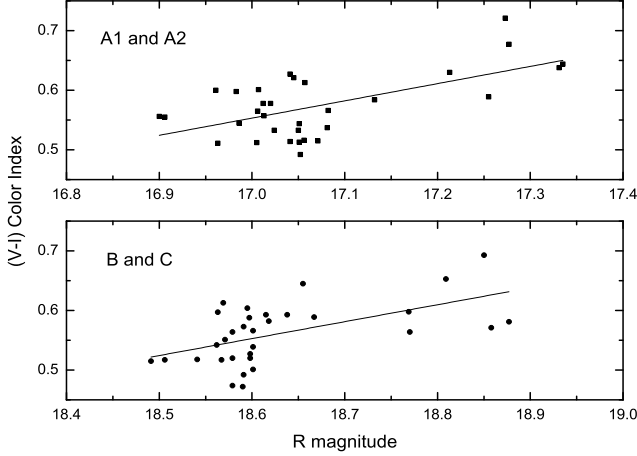


Figure 5. $V - I$ versus R diagrams for image A (upper panel) and B,C (bottom), illustrating a statistical dependence between the color indices and magnitudes. The regression line slopes differ insignificantly for the A1,A2 and B,C image pairs and equal 0.29 and 0.28, with the correlation indices 0.61 and 0.56, respectively.

axis by the values of the mean magnitude differences between the components. The values of $V - I$ grew with the growth of the R magnitude in both diagrams, with the regression line slopes of 0.28-0.29. This is qualitatively consistent with the total 0.4-mag fading of the PG1115+080 quasar during 2001-2005: according to numerous observations, there is a common tendency for many quasars to become bluer at their bright phases (see, e.g. Giveon et al. 1999 and references therein). In particular, Giveon et al. (1999) presented the $\Delta(B - R)$ versus ΔB and $\Delta(B - R)$ versus ΔR diagrams built for a subset of 21 quasars from their Palomar Green sample consisted of 42 quasars. Their diagrams show a significant correlation between the color and magnitude variations, with the regression line slopes of 0.25-0.27.

The regression line slopes for the diagrams in our Fig. 5 are also close to that reported for Q2237+0305 in one of our previous publications (Vakulik et al. 2004). There is an important difference between the two quadruple lenses, however: the Q2237+0305 light curves are strongly dominated by microlensing events, while in PG1115+080, a contribution from microlensing activity is small as compared to the quasar intrinsic variability. We do not see any significant difference between the two diagrams in Fig. 5, though the contributions from microlensing for these image pairs are different. Therefore, the diagrams in Fig. 5 should be referred to characteristics of the PG1115+080 quasar variability rather than to microlensing variability, in contrast to Q2237, where they result mostly from microlensing.

Also, we tried to analyze the long-term history of color changes in PG1115+080 and plotted the values of $V - I$ averaged within every season as functions of the corresponding time moments, which are the midpoints of the seasons (Fig. 6). It should be remembered that the values of color indices in this plot are accurate to only $\sim \pm 0.025$ mag, therefore, Fig. 6 illustrates their behaviors in time qualitatively rather than quantitatively. Nevertheless, though the data points in this plot are rather scattered and often overlap giving a rather intricate pattern, the general features in behaviors of color indices are evident. To make them clearer, we showed the corresponding linear approximations in Fig. 6. First we notice that the $V - I$ color indices increase in time for all the four image components. This conclusion seems to be valid, while the differences in

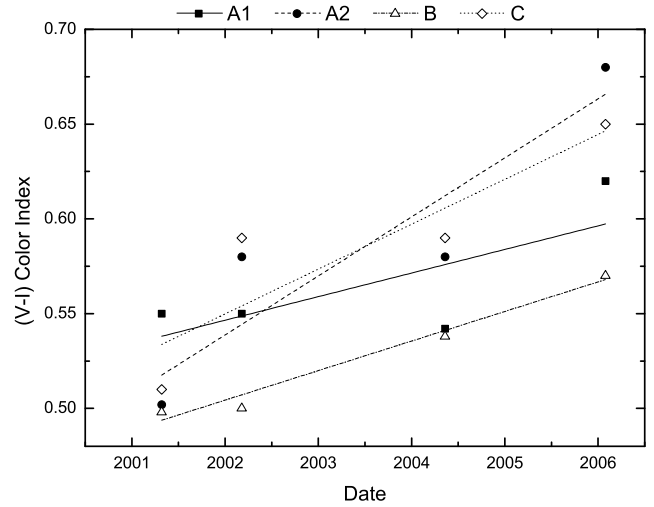


Figure 6. A history of the long-term variations of color indices $V - I$ in PG1115+080. Each point is a result of averaging of $V - I$ values within the corresponding season; the midpoints of every season are along the horizontal axis.

gradients of the $V - I$ colors with time are hardly veridical. In general, Fig. 6 confirms the dominating contribution from the quasar intrinsic variability over microlensing activity in PG 1115+080 light curves, as was indicated in the section above. Another significant conclusion from Fig. 6, is that the $V - I$ color index of image B remains permanently smaller than those of the three other ones, while demonstrating similar increase as well. We fail to explain why an image that lies the smallest distance from the lensing galaxy turned out to have the bluest color index.

4 ANALYSIS OF THE NEW ESTIMATES OF TIME DELAYS IN PG 1115+080

The time delays in PG 1115+080 were determined for the first time by Schechter et al. (1997) to be 23.7 ± 3.4 days between B and C, and 9.4 ± 3.4 days between A1+A2 and C (image C is leading). Barkana (1997) re-analyzed their data using another algorithm and reported $25^{+3.3}_{-3.8}$ days for the time delay between B and C, and this is quite consistent with 23.7 ± 3.4 days from Schechter et al. (1997). But the other time delays, and hence the time delay ratio $r_{ABC} = \tau_{AC}/\tau_{BA}$ differ significantly: $r_{ABC} = 1.13^{+0.18}_{-0.17}$ as calculated by Barkana (1997) and 0.7 ± 0.3 according to Schechter et al. (1997). Since 1997, just these values, either the first or the second ones, were being used to constrain the PG1115+080 model and determine the Hubble constant.

Determination of the time delays has generated a flow of models for the system, (Schechter et al. 1997, Keeton & Kochanek 1997, Courbin et al. 1997, Impey et al. 1998, Saha & Williams 2001, Kochanek, Keeton & McLeod 2001, Zhao & Pronk 2001, Chiba 2002, Treu & Koopmans 2002, Yoo et al. 2005, 2006, Pooley et al. 2006, Miranda & Jetzer 2007), all illustrating how strongly the estimated value of H_0 depends on the adopted mass profiles of the lens galaxy for the given values of time delays.

The detailed analysis of the uncertainties in determining Hubble constant from the time delay lenses can be found in, e.g., Kochanek & Schechter (2004), Schechter (2005), Kochanek (2002), where the paths to eliminate or at least to lessen the uncertainties have been also outlined. Kochanek & Schechter (2004)

Table 3. The time delays (days) for PG1115+080 as reported earlier and in our previous work, (Vakulik et al. 2009).

Author	τ_{BA}	τ_{AC}	τ_{BC}
Schechter (1997)	14.3 ± 3.4	9.4 ± 3.4	23.7 ± 3.4
Barkana (1997)	$11.7^{+2.9}_{-3.2}$	$13.3^{+2.0}_{-2.2}$	$25.0^{+3.3}_{-3.8}$
Vakulik (2009)	$4.4^{+3.2}_{-2.5}$	$12.0^{+2.5}_{-2.0}$	$16.4^{+3.5}_{-2.5}$

indicated, in particular, the importance of improving the accuracy of time delays for PG 1115+080.

The R light curves taken from the 2004-2006 data (Fig. 2) clearly demonstrate their applicability to determine the time delays. As compared to the data used by Schechter et al. (1997) and Barkana (1997), we were lucky to detect the quasar brightness variation with an amplitude of almost a factor of three larger, and with rather well-sampled data points within every season of observations. In addition, the accuracy of our photometry has made it possible to confidently detect flux variations with an amplitude as small as 0.05 mag that can be seen in the data of 2004.

The methodology to determine the time delays in pairs is simple enough and obvious. A common feature of all known methods of time delay measurements is the use, in one way or another, of the cross-correlation maximum or mutual dispersion minimum criteria, while they may differ in the algorithms of the initial data interpolation.

Analysis of the light curves of quasar images in pairs can also be applied when a lens consists of more than two images. To determine the time delays from the light curves shown in Fig. 2, we used another approach however, as described in more detail in our previous works (Vakulik et al. 2006, 2009). Here we shall only remind the fundamentals of our approach.

We determined the source light curve from a joint analysis of light curves of all image components. The individual time delays for pairs of images can be then determined with respect to this model source light curve jointly from the corresponding system of equations.

Since, according to predictions of all lens models and to measurements in X-rays by Dai et al. (2001) and Chartas et al. (2004), the time delay between images A1 and A2 does not exceed a small fraction of the day, their fluxes were summed to form a single curve, which we call the A light curve. Thus, we may write the following functional for three light curves:

$$\Phi(\Delta t, \tau_0, \tau_1, \tau_2) = \frac{1}{3N} \sum_{j=0}^2 \sum_{i=0}^N \frac{[m_j(t_i) + dm_j - f(t_i, \Delta t, \tau_j)]^2}{\sigma_j^2(t_i)}, \quad (3)$$

where $m_j(t_i)$ are the data points in the light curve of the j th image at the time moments t_i ; dm_j and τ_j are the shifts of a corresponding light curve in stellar magnitude and in time, respectively, N is a number of points in the light curves, Δt is the parameter of the approximating function $f(t_i, \Delta t, \tau_j)$, and $\sigma_j^2(t_i)$ are the photometry errors.

We adopted $dm_0 = 0$ and $\tau_0 = 0$ in our calculations, that is, we fitted the light curves of B and C to the A light curve, and thus, dm_1 and dm_2 are the magnitude differences A–B and A–C, respectively. At given values of τ_1 and τ_2 , we minimize $\Phi(\Delta t, \tau_1, \tau_2)$ in dm_j and in coefficients of the approximating function. The values of minimum of $\Phi(\Delta t, \tau_1, \tau_2)$ were being looked for at a rectangular mesh τ_1, τ_2 with a step of 0.5 d in preliminary calculations, and of 0.2 d

Table 4. Time delay ratios τ_{AC}/τ_{BA} and τ_{AC}/τ_{BC} for PG1115+080 as predicted by several lens models (the upper part of the table) and determined from the existing measurements of the time delays for the system (the last three lines).

Author	τ_{AC}/τ_{BA}	τ_{AC}/τ_{BC}
Schechter et al. (1997)	1.33-1.80	0.57-0.64
Keeton&Kochanek (1997)	1.35-1.47	–
Impey et al. (1998)	1.3	–
Chartas et al. (2004)	1.3	0.56
Keeton et al. (2009)	1.54	0.61
Schechter et al. (1997)	0.66	0.40
Barkana (1997)	1.14	0.53
Vakulik et al. (2009)	2.73	0.73

at a final stage. The values of τ_1, τ_2 corresponding to the minimal value of $\Phi(\Delta t, \tau_1, \tau_2)$ were adopted as the estimates of the time delays τ_{BA} and τ_{AC} . Fig. 7 shows a distribution of $\Phi(\Delta t, \tau_1, \tau_2) - \Phi_{min}$ in the space of parameters τ_{BA} and τ_{AC} calculated for parameter $\Delta t = 0.12$ years. Thus, our estimates of the time delays that can be read out at the τ_{AC} and τ_{BC} axes against the centre of contours in Fig. 7, are $\tau_{BA} = 4.4$, $\tau_{AC} = 12.0$ days. The time delay τ_{BC} is not an independent quantity in our method, and can be determined as a linear combination $\tau_{BC} = \tau_{BA} + \tau_{AC}$, that is, $\tau_{BC} = 16.4$ days.

To test our method for robustness and absence of systematics, and to estimate the accuracy inherent in our time delay measurements, we fulfilled a numerical simulation as described in detail in (Vakulik et al. 2009). The simulated light curves of the components were obtained by shifting the approximating curve $f(t_i, \Delta t, \tau_j)$ by the proper time delays τ_1, τ_2 and magnitude differences, and by adding random quantities to imitate the photometry errors. We simulated 2000 light curves synthesized as described above, and calculated the resulting time delays using the procedure, which was exactly the same as in the analysis of the actual light curves. The results of simulations were used to build the distribution functions for errors and to estimate the 95-percent confidence intervals.

The final values of the time delays and the corresponding uncertainties are presented in Table 3, where they can be compared with the estimates reported by Schechter et al. (1997) and Barkana (1997).

It is interesting to note that using only the data of 2004, where a small-amplitude turn-over in the light curves is detected, we obtained $\tau_{BA} = 5.0$ days, $\tau_{AC} = 9.4$ days, and $\tau_{BC} = 14.4$ days, consistent with the estimates obtained from the whole data set. However, simulation of errors for only the data of 2004 demonstrates noticeably larger uncertainties, as compared to those calculated from the entire light curve.

The light curves of images A, B and C shifted by the corresponding time delays and reduced to image A in magnitude are shown in figure 2 from our previous paper (Vakulik et al 2009) for the approximating function parameter $\Delta t = 0.12$ years. As is seen from this picture, the data points for all the three images are very well consistent with each other and with the approximating curve.

Thus we obtained the time delay values, which differ noticeably from those reported by Schechter et al. (1997) and Barkana (1997) and used in a variety of models of many authors to derive the Hubble constant value. The largest differences are for τ_{BC} and τ_{BA} : our estimate of τ_{BC} is a factor of 1.5 smaller, while for τ_{BA} , it is almost three times smaller as compared to the results of Schechter (1997) and Barkana (1997). Meanwhile, our values

Table 5. Time delays as predicted by the lens models calculated by Schechter et al.(1997) and the values of the Hubble constant H_0 obtained from comparison of these time delays with those obtained by Schechter et al. (1997), columns 2-4; the H_0 values calculated for the same lens models with the time delays determined in this work (columns 5-7).

Lens models, τ (days) and H_0 (Schechter et al.1997)				H_0 with τ_{AC} and τ_{BC} from this work		
Model	$\tau_{AC}(\text{days})$	$\tau_{BC}(\text{days})$	$H_0(\text{km s}^{-1}\text{Mpc}^{-1})$	H_0 ($\tau_{AC} = 12.0^d$)	$H_0(\tau_{BC} = 16.4^d)$	$H_0(\text{mean})$
PMXS	12.5	19.9	84	104	121	113
ISXS	6.6	10.4	44	55	63	59
ISEP	9.7	15.1	64	81	92	86
ISIS	5.6	9.7	41	47	59	53
ISIS+	5.7	10	42	48	61	54

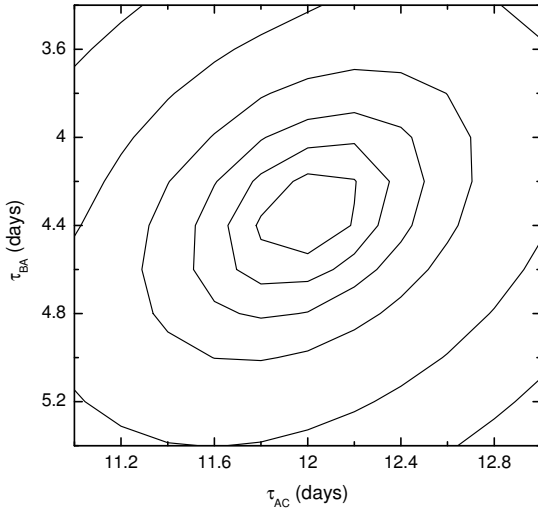


Figure 7. Distribution of $\Phi(\Delta t, \tau_1, \tau_2) - \Phi_{min}$ in the space of parameters τ_{AC} and τ_{AB} . The innermost contour corresponds to $\Phi(\Delta t, \tau_1, \tau_2) - \Phi_{min}$ equalling 0.0001, with every next level twice as much than preceding.

of τ_{AC} are rather similar to those of Schechter and, especially, of Barkana.

As is noted in Introduction, the time delay between one of the image pairs, say, τ_{BC} , can be used to determine H_0 , while the time delay ratio $r_{ABC} = \tau_{AC}/\tau_{BA}$ is independent of the H_0 value and can be used to constrain the lens model. Most of the PG1115+080 macromodels are consistent in predicting r_{ABC} to within 0.15. As far as can be expected from Table 3, the three measurements of time delays do not provide the time delay ratios consistent with each other and with model predictions. This can be seen from Table 4, where we collected several model predictions for r_{ABC} together with the measurements presented by Schechter et al. (1997), Barkana (1997) and Vakulik et al. (2009). Also, we presented here the time delay ratios $r_{CBA} = \tau_{AC}/\tau_{BC}$, which are connected with r_{ABC} by a relationship $r_{CBA} = r_{ABC}/(1 + r_{ABC})$. These quantities demonstrate better agreement between model predictions and measurements.

The time delay ratios calculated from measurements of Schechter and Barkana are seen to be lower as compared to the model predictions, while our measurements provide the estimates of this quantities exceeding the model predictions, especially for $r_{ABC} = \tau_{AC}/\tau_{BA}$, which is as large as 2.73 from our data. One should admit that such discrepancy is too large, since the largest r_{ABC} we have found in the literature is that calculated by Schechter et al. (1997) for their isothermal ellipsoid model - $r_{ABC} = 1.8$.

The reason for this becomes qualitatively clear when addressing the data in Table 3: the shortest time delay τ_{BA} is measured with

almost the same absolute error as the longest one, τ_{BC} , that is, of all the three time delays, τ_{BA} has the largest relative error. Therefore, we are far from arguing our value of τ_{BA} to be more trustworthy than those obtained by Schechter and Barkana. We regard, however, that the values of τ_{BC} and τ_{AC} are more reliable and trustworthy. Also, it should be noted that none of the macrolens models we could find in the literature predicts the values of τ_{BC} larger than 18d, - the value 19.9d from the unrealistic point-mass model in Schechter et al. (1997) may hardly be taken into account.

In the framework of the present publication, we did not intend to either propose an extra exotic lens model or recalculate the most popular ones to derive the new estimate of the Hubble constant, but instead, we have made use of the results of Schechter et al. (1997), who calculated five models for the gravitational potential of PG1115+080. The time delays τ_{AC} and τ_{BC} as predicted by their five models for $\Omega = 1$ and $H_0 = 100\text{km s}^{-1}\text{Mpc}^{-1}$, and the corresponding estimates of H_0 obtained with their time delays are shown in Table 5 (columns 2-4). We remind that, according to Schechter et al. (1997), model PMXS means a point mass with external shear, the ISXS model is an isothermal sphere with external shear, and ISEP is an isothermal elliptical potential. The ISIS model uses a second isothermal sphere for a group of galaxies at approximately the same redshift as the main lensing galaxy (Young et al. 1981; Henry & Heasley 1986) to represent shear. In the ISIS+ model, the uncertainty in the galaxy position is not regarded to be negligible, as in the ISXS and ISIS, but its coordinates were taken as two additional free parameters.

Columns 5 to 7 of Table 5 contain the H_0 values estimated for the Schechter et al. models with our values of the time delays for image pairs AC and BC separately (column 5 and 6), and the average between the pairs (column 7). We may conclude that, as could be expected, our new estimates of τ_{BC} and τ_{AC} provide higher values of Hubble constant, which are closer to the most recent value obtained in the HST Key Project from observations of Cepheids (Freedman et al. 2001).

5 DISCUSSION AND CONCLUSIONS

From our new data of excellent quality, we had a possibility to discriminate between the quasar intrinsic and microlensing brightness and color variations for PG 1115+080, and to obtain new estimates of the time delays. It may immediately be seen from our R light curves, especially for 2004-6 seasons, that significant brightness fluctuations with amplitudes exceeding the typical error bars of the data points, have been detected. This allows us to recompute the values of H_0 calculated with the previous estimates of the time delays for this gravitational lens system.

In particular, we find the following:

- We have studied behaviors of brightness ratios of all the components both in time and in wavelength. We report microlensing in A1 with an amplitude of about 0.3 mag in filter *R* on a time-scale of 25 years. The magnification peak in A1 took place in 1992-1995, with the subsequent fading in 2001-2006. The image A1 flux may be expected to reach its undisturbed value by 2006 or later. A microlensing event was apparently observed in image A2 as well, with its rising branch in 2001-2005, when image A2 brightened by approximately 0.15 mag. The time scales and amplitudes of both events are consistent with those predicted for this object for the Solar mass microlenses (Schechter 2004). We also notice that a similar microlensing amplitude was detected for another quasar with similar redshift distances to the quasar and lens, - for the First Lens Q0957+561 (Schild & Smith 1991). In fitting the 2004-2006 data points to the approximating function, very subtle signs of microlensing have also been found in image B.

- Therefore, deviation of the observed A2/A1 flux ratio from that predicted by most of the lens models can be well explained by microlensing events. An additional contribution to the flux ratio "anomaly" may be expected from the source position with respect to the caustic fold: when expressed in terms of R_{fold} (Eq. 2), the brightness difference between A1 and A2 would equal 0.08, which means that, according to simulations of KGP (2005), it is within a region admissible by a smooth lensing potential model, that is, it is not anomalous in the sense implied first by Mao & Schneider (1998).

- We have made use of observations in other filters available for some dates to analyse behaviors of color indices of the images. The $V - I$ versus R diagrams built for pairs A1+A2 and B+C demonstrate the known tendency of quasars to become bluer at their bright phases, with no signs of any contribution from microlensing: the diagrams for both image pairs are nearly identical. This can be explained either by poor statistics (the data in all the three filters are available for only 16 nights, providing rather poor correlation as indicated in Fig. 5 caption), or by small amplitudes of the microlensing events under consideration, or by both reasons.

- An interesting feature of the behaviours of color indices should be noted. While all images demonstrate growth of their color indices in time, the $V - I$ color indices of image B are slightly but steadily less than those of other images. This is rather unexpected, since image B is located the closest distance to the main lensing galaxy.

- The time delays for PG1115+080 obtained from our monitoring data in 2004-2006 differ from those determined by Schechter et al. (1997) and Barkana (1997) earlier. The differences for τ_{BA} and τ_{BC} are well beyond the uncertainties reported in both publications and determined in the present work. While our time delay estimates for images A and C are rather close to the two previous ones, the delays for two other image pairs can not be regarded as consistent even marginally.

- As could be expected, our estimates of time delays τ_{AC} and τ_{BC} result in larger H_0 values than those reported by Schechter et al. (1997) with their estimates of time delays and with the ISXS, ISIS and ISIS+ models by Schechter et al. (1997). The new estimates of H_0 are more consistent with the most recent H_0 value obtained in the HST Key project (Freedman et al. 2001).

- The new estimates of time delays in PG1115+080 provide additional support for the family of models close to isothermal. As analyzed in details by Kochanek and Schechter (2004), the estimates of H_0 with the use of time delay lenses are bounded by two

limiting models: models with less dark matter (more centrally concentrated mass profiles) produce higher values of H_0 than those with more dark matter. In particular, the constant mass-to-light ratio models set an upper limit on estimates of H_0 , while the isothermal mass distribution models are responsible for the lower limit of H_0 . Our result is very important in this respect, since an isothermal model is preferred for the lensing galaxy in PG1115+080 for the reasons listed by Schechter (2005): (1) the velocity dispersions observed for an ensemble of lensing galaxies are consistent with the fundamental plane relations for ellipticals; (2) a majority of the nearby galaxies, as well as those lensing galaxies for which the radial mass distributions can be measured, are very nearly isothermal. Since the PG1115+080 lensing galaxy is by no means unusual, the isothermal hypothesis is most probable.

In conclusion, recently published (Morgan et al. 2008) observations of PG 115+080 in filter *R* during almost exactly the same time periods in 2004-2006 should be mentioned. We have used their table 3 photometry to compare to our light curves. The quasar brightness fluctuations which allowed us to determine the time delays are seen in their A1+A2 light curve quite well, but become undetectable in the B and C light curves because of a much larger scatter of the data points.

ACKNOWLEDGEMENTS

The authors from Ukraine and Uzbekistan are grateful to the Science and Technology Center in Ukraine (STCU grant U127) which made possible observations at the Maidanak Observatory and the further processing of the data. The authors from Ukraine thank also the National Program "CosmoMicroPhysics", and the authors from Uzbekistan are thankful to the DFG grant 436 Usb 113/5/0-1. This work has been also supported by the Russian Foundation for Basic Research (RFBR) grant No.09-02-00244 and No.06-02-16857.

Also, the authors would like to express their sincere gratitude to the anonymous referee for very constructive and helpful comments.

REFERENCES

- Barkana R. 1997, ApJ 489, 21
- Blandford R, Narayan R. 1986 ApJ, 310, 568
- Bradač M., Schneider P., Steinmetz M., Lombardi M., King L. J., Porcas R. 2002, A&A 388, 373
- Chartas G., Dai X., Garmire G.P. 2004, Carnegie Observatories Astrophysics Series, Ed. W.L.Freedman, v. 2, p.1
- Chiba M. 2002, ApJ 565, 17
- Chiba M., Minezaki T., Kashikawa N., Hirokazu K., Kaiki T. I. 2005, ApJ 627, 53
- Christian C.A., Crabtree D., Waddell P. 1987, ApJ 312, 45
- Congdon A.B., Keeton Ch.R. 2005, MNRAS 364, 1459
- Courbin F., Magain P., Keeton C.R., Kochanek C.S., Vanderriest C., Jaunsen A.O., Hjorth J. 1997, A&A 324, L1
- Dai, X., Chartas G., Garmire G. P., Bautz M. W. 2001, BAAS 33, 1334
- Dalal N., Kochanek C. S. 2002, ApJ 572, 25
- Freedman W.L., et al. 2001, ApJ 553, 47
- Giveon U., Maoz D., Kaspi Sh., Netzer H., Smith P.S. 1999, MNRAS 306, 637
- Hege E.K., Hubbard E.N., Strittmatter P.A., Worden S.P. 1980, Nat. 287, 416

- Henry J.R., Heasley J.N. 1986, *Nat.* 321, 139
- Impey C.D., Falco E.E., Kochanek C.S., Lehar J., McLeod B.A., Rix H.-W., Peng C.Y., Keeton C.R. 1998 *ApJ*, 509, 551
- Keeton Ch.R. 2001 *ApJ*, 562, 46
- Keeton C.R., Gaudi B.S., Petters A.O. 2003, *ApJ* 598, 138
- Keeton Ch.R., Gaudi B.S., Petters A.O. 2005 *ApJ*, 635, 35
- Keeton C.R., Kochanek C.S., Seljak U. 1997, *ApJ* 482, 604
- Keeton C.R., Kochanek C.S. 1997, *ApJ* 487, 42
- Keeton C.R., Moustakas L.A. 2009, *ApJ* 699, 1720
- Kent S.M., Falco E.E. 1988, *AJ* 96, 1570
- Klypin A., Kravtsov A., Valenzuela O. 1999, *ApJ* 522, 82
- Kochanek C.S. 1991, *ApJ* 373, 354
- Kochanek C.S. 2002, *ApJ* 578, 25
- Kochanek C.S., Dalal N. 2004, *ApJ* 610, 69
- Kochanek C.S., Keeton C.R., McLeod B.A. 2001, *ApJ* 547, 50
- Kochanek Ch.S., Schechter P.L. *Carnegie Observatories Centennial Symp.* Cambridge Univ. Press, *Carnegie Observatories Astrophysics Series*. Edited by W. L. Freedman, 2004, p. 117.
- Kristian J., et al. 1993, *AJ* 106, 1331
- Lucy L.B. 1974, *AJ* 79, 745
- Mao Sh. 1992, *AJ* 389, 63
- Mao Sh., Jing Y., Ostriker J.P., Weller J. 2004, *ApJ* 604, L5
- Mao Sh., Schneider P. 1998, *MNRAS* 295, 587
- Metcalfe R.B., Madau P. 2001, *ApJ* 563, 9
- Metcalfe R.B., Zhao H.Sh. 2002, *ApJ* 567, L5
- Miranda M., Jetzer P. 2007, *Ap&SS*, 312, 203
- Moore B., Calcanoe-Roldan C., Stadel J., Quinn T., Lake G., Ghigna S., Governato F. 2001, *Phys.Rev.* 64, No.6, 301
- Morgan C.W., Kochanek C.S., Dai X., Morgan N.D., Falco E.E. 2008, *ApJ* 689, 755
- Oguri M. 2007, *ApJ* 660, 1
- Pooley D., Blackburne J.A., Rappaport S., Schechter P.L., Fong W.-F. 2006 *ApJ*, 648, 67
- Pooley D.A., Blackburne J.A., Rappaport S., Schechter P.L. 2007, *ApJ* 661, 19
- Pooley D., Rappaport S., Blackburne J., Schechter P.L., Schwab J., Wambsganss J. 2009, *ApJ* 697, 1892
- Read J. I., Saha P.; Macciò A. V. 2007, *ApJ* 667, 645
- Refsdal S. 1964, *MNRAS* 128, 307
- Richardson W.H. 1972, *JOSA* 62, 55
- Saha P., Williams L.L.R. 1997, *MNRAS* 292, 148
- Saha P., Coles J., Macciò A.V., Williams L.L.R. 2006, *ApJ* 650, L17
- Schechter P.L., 1993, in J. Surdej, D. Fraipont-Caro, E. Gosset, S. Refsdal, and M. Remy, eds, *Proc. 31st Liege Internat. Astroph. Coll., Gravitational Lenses in the Universe*. Universite de Liege, Institut d'Astrophysique, Liege, p.119
- Schechter P.L., et al. 1997, *ApJ* 475, L85
- Schechter P.L. *IAU Symposium*, vol. 225. Edited by Y. Mellier and G. Meylan. Cambridge, UK: Cambridge University Press, 2005, 281
- Schechter P., Wambsganss J. 2002, *ApJ* 580, 685
- Schild R.E., Smith R.Ch. 1991, *ApJ* 101, 813
- Schneider P., Ehlers J., Falco E.E. 1992, *Gravitational lenses* (Berlin: Springer)
- Schneider P., Weiss A. 1992, *A&A* 260, 1
- Tonry J.L. 1998, *AJ* 115, 1
- Treu T., Koopmans V.E. 2002, *MNRAS* 337, L6
- Vakulik V., et al. 2004, *A&A*, 420, 447
- Vakulik V., Schild R., Dudinov V., Nuritdinov S., Tsvetkova V., Burkhonov, O., Akhunov, T. 2006, *A&A*, 447, 905
- Vakulik V.G., et al. 2009, *MNRAS* 400, L90
- Vanderriest C., Wlérick G., Lelièvre G., Schneider J., Sol H., Horville D., Renard L., Servan B. 1986, *A&A* 158, L5
- Weymann R.J., et al. 1980, *Nature* 285, 641
- Williams L. L. R., Saha P. 2000, *AJ* 119, 439
- Witt H.J., Mao Sh., Keeton Ch.R. 2000, *ApJ* 544, 98
- Young P., Deverill R.S., Gunn J.E., Westphall J.A., Kristian J. 1981, *ApJ* 244, 729
- Yoo J., Kochanek C.S., Falco E.E., McLeod B.A. 2005, *ApJ* 626, 51
- Zhao H.Sh., Pronk D. 2001, *MNRAS* 320, 401

Table 6. Photometry of the PG1115+030 images in filter V.

Date	JD	Seeing (arcsec)	A1	A2	B	C
20-04-2001	2452019	1.47	17.025±0.097	17.025±0.079	18.8±0.09	18.232±0.088
26-04-2001	2452025	1.258	16.868±0.021	17.19±0.017	18.736±0.02	18.296±0.019
27-04-2001	2452026	1.287	16.874±0.037	17.214±0.03	18.781±0.035	18.298±0.034
03-03-2002	2452336	1.171	16.889±0.024	17.252±0.019	18.782±0.022	18.406±0.022
08-03-2002	2452341	1.198	16.985±0.046	17.215±0.038	18.819±0.044	18.435±0.043
17-01-2004	2453021	1.038	16.972±0.007	17.185±0.006	18.782±0.007	18.403±0.007
13-02-2004	2453048	1.236	17.0 ±0.02	17.248±0.017	18.815±0.019	18.424±0.018
22-02-2004	2453057	1.262	16.973±0.026	17.28±0.022	18.843±0.024	18.412±0.024
26-02-2004	2453061	1.029	17.04±0.014	17.221±0.012	18.828±0.013	18.418±0.013
27-02-2004	2453062	0.845	17.005±0.004	17.243±0.003	18.831±0.004	18.404±0.004
28-02-2004	2453063	1.15	17.021±0.019	17.224±0.016	18.856±0.018	18.41±0.018
01-03-2004	2453065	1.059	17.008±0.014	17.237±0.012	18.832±0.013	18.404±0.013
10-04-2004	2453105	1.02	16.934±0.006	17.187±0.005	18.775±0.006	18.353±0.006
11-04-2004	2453106	1.183	16.939±0.013	17.187±0.011	18.792±0.012	18.356±0.012
14-04-2004	2453109	0.947	16.947±0.005	17.168±0.004	18.754±0.005	18.352±0.005
03-05-2004	2453128	1.203	16.932±0.03	17.196±0.024	18.699±0.028	18.38±0.028
09-05-2004	2453134	0.842	16.96±0.004	17.214±0.003	18.751±0.004	18.405±0.003
13-05-2004	2453138	0.842	16.972±0.005	17.218±0.004	18.772±0.005	18.401±0.005
17-05-2004	2453142	1.322	16.942±0.026	17.262±0.022	18.829±0.025	18.437±0.024
26-05-2004	2453151	1.169	16.95±0.023	17.279±0.019	18.792±0.022	18.414±0.022
04-06-2004	2453160	1.347	17.077±0.027	17.172±0.022	18.806±0.025	18.438±0.025
08-06-2004	2453164	1.233	17.11±0.032	17.145±0.027	18.845±0.03	18.482±0.029
05-01-2006	2453740	1.038	17.316±0.008	17.561±0.006	19.09±0.007	18.72±0.007
08-03-2006	2453802	1.093	17.313±0.011	17.526±0.009	19.083±0.01	18.657±0.01
15-04-2006	2453840	0.979	17.2 ±0.01	17.453±0.008	18.977±0.009	18.576±0.009

Table 7. Photometry of the PG1115+030 images in filter I.

Date	JD	Seeing (arcsec)	A1	A2	B	C
26-04-2001	2452025	1.197	16.313±0.026	16.698±0.021	18.262±0.025	17.781±0.024
27-04-2001	2452026	1.144	16.318±0.018	16.699±0.015	18.261±0.018	17.781±0.017
03-03-2002	2452336	1.01	16.362±0.012	16.654±0.01	18.282±0.011	17.817±0.011
04-03-2002	2452337	1.351	16.421±0.07	16.578±0.058	18.337±0.066	17.845±0.065
05-03-2002	2452338	0.858	16.35 ±0.018	16.662±0.014	18.312±0.017	17.793±0.016
07-03-2002	2452340	1.288	16.371±0.037	16.695±0.03	18.317±0.034	17.841±0.034
08-03-2002	2452341	1.139	16.399±0.035	16.661±0.028	18.285±0.032	17.836±0.032
11-03-2002	2452344	1.043	16.417±0.023	16.66 ±0.019	18.329±0.021	17.853±0.021
14-03-2002	2452347	0.928	16.42 ±0.015	16.67 ±0.012	18.333±0.014	17.828±0.014
11-04-2004	2453106	1.136	16.427±0.01	16.622±0.008	18.265±0.01	17.814±0.01
14-04-2004	2453109	0.773	16.414±0.005	16.623±0.004	18.262±0.005	17.801±0.005
03-05-2004	2453128	1.125	16.418±0.031	16.598±0.026	18.182±0.029	17.767±0.029
09-05-2004	2453134	0.747	16.427±0.005	16.636±0.004	18.25 ±0.005	17.832±0.005
13-05-2004	2453138	0.765	16.428±0.005	16.64 ±0.005	18.252±0.005	17.835±0.005
17-05-2004	2453142	1.166	16.426±0.021	16.661±0.017	18.265±0.02	17.833±0.019
26-05-2004	2453151	1.057	16.437±0.016	16.652±0.013	18.253±0.015	17.832±0.015
04-06-2004	2453160	1.222	16.464±0.054	16.606±0.045	18.213±0.051	17.845±0.05
08-06-2004	2453164	1.049	16.526±0.027	16.588±0.023	18.256±0.026	17.837±0.025
05-01-2006	2453740	1.046	16.672±0.009	16.84 ±0.007	18.509±0.008	18.026±0.008
08-03-2006	2453802	0.972	16.675±0.008	16.849±0.007	18.512±0.008	18.004±0.008
15-04-2006	2453840	0.804	16.611±0.006	16.823±0.005	18.413±0.005	17.978±0.005

Table 8: Photometry of the PG 1115+030 images in filter *R*.

Date	JD	Seeing (arcsec)	A1	A2	B	C
20-04-01	2452019	1.226	16.625±0.011	17.069±0.009	18.573±0.011	18.095±0.01
26-04-01	2452025	1.277	16.636±0.013	17.052±0.01	18.579±0.012	18.091±0.012
27-04-01	2452026	1.126	16.63 ±0.008	17.071±0.007	18.579±0.008	18.106±0.008
03-03-02	2452336	1.065	16.693±0.014	17.045±0.011	18.59 ±0.013	18.197±0.013
04-03-02	2452337	1.359	16.687±0.038	17.079±0.031	18.688±0.036	18.215±0.035
08-03-02	2452341	1.204	16.691±0.049	17.081±0.04	18.541±0.046	18.163±0.046
11-03-02	2452344	1.266	16.713±0.034	17.081±0.028	18.59 ±0.032	18.178±0.031
17-01-04	2453021	1.27	16.762±0.031	17.011±0.026	18.574±0.029	18.195±0.029
21-01-04	2453025	1.45	16.785±0.034	16.998±0.029	18.612±0.032	18.186±0.032
22-01-04	2453026	0.81	16.767±0.004	17.009±0.004	18.596±0.004	18.194±0.004
10-02-04	2453045	1.254	16.832±0.027	17.015±0.023	18.62 ±0.026	18.205±0.025
13-02-04	2453048	1.174	16.799±0.019	17.041±0.015	18.611±0.018	18.219±0.017
16-02-04	2453051	1.451	16.787±0.036	17.087±0.03	18.644±0.034	18.206±0.034
22-02-04	2453057	1.361	16.832±0.037	17.016±0.031	18.652±0.035	18.221±0.034
26-02-04	2453061	1.065	16.841±0.021	17.007±0.018	18.667±0.02	18.216±0.02
27-02-04	2453062	0.828	16.799±0.004	17.032±0.003	18.625±0.004	18.202±0.004
28-02-04	2453063	1.225	16.766±0.028	17.072±0.023	18.578±0.026	18.177±0.026
01-03-04	2453065	1.075	16.813±0.018	17.02 ±0.015	18.652±0.017	18.205±0.017
30-03-04	2453094	1.157	16.803±0.013	17.013±0.011	18.64 ±0.012	18.16 ±0.012
08-04-04	2453103	1.208	16.772±0.01	16.983±0.008	18.615±0.01	18.166±0.01
10-04-04	2453105	1.033	16.754±0.005	16.985±0.004	18.597±0.005	18.163±0.005
11-04-04	2453106	1.032	16.735±0.006	17.006±0.005	18.598±0.006	18.162±0.006
12-04-04	2453107	1.145	16.747±0.011	16.991±0.009	18.578±0.011	18.148±0.01
14-04-04	2453109	0.927	16.754±0.004	16.986±0.003	18.591±0.004	18.171±0.004
03-05-04	2453128	1.134	16.771±0.023	16.983±0.019	18.567±0.022	18.169±0.021
09-05-04	2453134	0.761	16.78 ±0.003	17.012±0.003	18.601±0.003	18.191±0.003
13-05-04	2453138	0.827	16.781±0.004	17.02 ±0.003	18.598±0.004	18.201±0.003
17-05-04	2453142	1.244	16.786±0.017	17.007±0.014	18.579±0.016	18.195±0.016
26-05-04	2453151	1.005	16.781±0.013	17.041±0.011	18.601±0.012	18.218±0.012
04-06-04	2453160	1.144	16.787±0.013	17.082±0.011	18.615±0.012	18.238±0.012
08-06-04	2453164	1.138	16.862±0.023	17.013±0.019	18.667±0.022	18.255±0.022
08-02-05	2453409	0.84	17.018±0.004	17.258±0.003	18.83 ±0.004	18.422±0.004
13-02-05	2453414	1.192	17.06 ±0.011	17.26 ±0.009	18.87 ±0.01	18.442±0.01
14-02-05	2453415	1.344	17.021±0.018	17.256±0.015	18.842±0.017	18.427±0.017
16-02-05	2453417	1.461	17.08 ±0.049	17.268±0.041	18.941±0.047	18.439±0.046
20-02-05	2453421	0.888	17.042±0.007	17.263±0.005	18.868±0.006	18.431±0.006
27-02-05	2453428	1.011	17.027±0.01	17.322±0.008	18.867±0.01	18.438±0.01
28-02-05	2453429	1.185	17.038±0.015	17.29 ±0.012	18.89 ±0.014	18.422±0.014
01-03-05	2453430	1.232	17.05 ±0.013	17.258±0.011	18.878±0.012	18.433±0.012
02-03-05	2453431	0.902	17.036±0.006	17.282±0.005	18.864±0.005	18.424±0.005
04-03-05	2453433	1.017	17.044±0.006	17.272±0.005	18.869±0.005	18.419±0.005
05-03-05	2453434	0.944	17.046±0.006	17.294±0.004	18.878±0.005	18.438±0.005
19-03-05	2453448	1.097	17.057±0.008	17.289±0.007	18.872±0.007	18.435±0.007
21-03-05	2453450	0.944	17.037±0.009	17.271±0.008	18.86 ±0.009	18.412±0.009
13-04-05	2453473	1.168	17.017±0.01	17.324±0.008	18.852±0.009	18.431±0.009
14-04-05	2453474	0.948	17.063±0.004	17.251±0.004	18.848±0.004	18.439±0.004
17-04-05	2453477	1.016	17.06 ±0.011	17.306±0.009	18.872±0.01	18.448±0.01
02-05-05	2453492	1.348	17.047±0.029	17.357±0.024	18.866±0.027	18.489±0.027
10-05-05	2453500	1.161	17.101±0.012	17.323±0.01	18.892±0.011	18.492±0.011
16-05-05	2453506	1.11	17.1 ±0.016	17.328±0.013	18.904±0.014	18.5 ±0.014
20-05-05	2453510	1.208	17.101±0.027	17.367±0.022	18.943±0.025	18.508±0.025
03-06-05	2453524	1.145	17.123±0.018	17.352±0.015	18.944±0.017	18.516±0.017
05-06-05	2453526	1.381	17.225±0.041	17.257±0.035	18.965±0.039	18.556±0.038
06-06-05	2453527	1.316	17.231±0.03	17.246±0.025	18.964±0.028	18.549±0.028
20-06-05	2453541	1.421	17.188±0.104	17.329±0.087	18.985±0.098	18.565±0.097
14-12-05	2453718	0.824	17.116±0.006	17.305±0.005	18.922±0.006	18.46 ±0.005
15-12-05	2453719	1.111	17.12 ±0.008	17.294±0.007	18.915±0.008	18.456±0.008
19-12-05	2453723	1.181	17.111±0.018	17.298±0.015	18.911±0.016	18.463±0.016

20-12-05	2453724	1.072	17.09 ±0.023	17.306±0.019	18.881±0.022	18.421±0.022
05-01-06	2453740	1.061	17.085±0.007	17.273±0.006	18.877±0.006	18.45 ±0.006
07-01-06	2453742	1.273	17.104±0.026	17.254±0.022	18.876±0.024	18.451±0.024
23-01-06	2453758	1.11	17.086±0.008	17.286±0.007	18.877±0.008	18.451±0.008
31-01-06	2453766	1.498	17.138±0.115	17.226±0.096	18.865±0.108	18.509±0.106
07-02-06	2453773	0.954	17.072±0.004	17.273±0.004	18.84 ±0.004	18.441±0.004
21-02-06	2453787	0.948	17.058±0.004	17.295±0.003	18.852±0.004	18.428±0.004
27-02-06	2453793	1.407	17.069±0.018	17.27 ±0.015	18.862±0.017	18.439±0.017
08-03-06	2453802	0.972	17.061±0.007	17.277±0.006	18.858±0.007	18.409±0.007
11-03-06	2453805	0.989	17.032±0.02	17.282±0.016	18.805±0.019	18.349±0.018
19-03-06	2453813	0.932	17.038±0.006	17.257±0.005	18.826±0.006	18.374±0.006
02-04-06	2453827	0.902	17.014±0.004	17.227±0.004	18.821±0.004	18.373±0.004
03-04-06	2453828	1.264	17.0 ±0.013	17.223±0.011	18.801±0.012	18.365±0.011
05-04-06	2453830	1.373	17.035±0.021	17.183±0.017	18.845±0.019	18.363±0.019
12-04-06	2453837	1.025	17.01 ±0.013	17.174±0.011	18.782±0.013	18.348±0.012
13-04-06	2453838	1.166	17.0 ±0.02	17.189±0.017	18.783±0.019	18.315±0.018
15-04-06	2453840	0.884	16.985±0.006	17.213±0.005	18.77 ±0.006	18.369±0.006
18-04-06	2453843	0.99	16.986±0.005	17.205±0.004	18.771±0.005	18.355±0.005
25-04-06	2453850	0.918	16.987±0.004	17.197±0.004	18.77 ±0.004	18.355±0.004
03-05-06	2453858	1.229	16.983±0.099	17.152±0.083	18.87 ±0.094	18.386±0.092
10-05-06	2453865	0.914	16.976±0.007	17.204±0.006	18.761±0.006	18.351±0.006
13-05-06	2453868	0.942	16.976±0.006	17.191±0.005	18.755±0.006	18.349±0.006
17-05-06	2453872	1.093	16.965±0.007	17.205±0.006	18.732±0.007	18.344±0.007
20-05-06	2453875	1.438	17.068±0.056	17.093±0.047	18.734±0.053	18.394±0.052
23-05-06	2453878	1.428	16.956±0.025	17.228±0.02	18.749±0.023	18.379±0.023
02-06-06	2453888	1.189	16.967±0.012	17.218±0.01	18.748±0.011	18.34 ±0.011